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Experimental evaluation of a solar thermoelectric cooled ceiling combined with displacement ventilation system

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ABSTRACT

A novel solar thermoelectric cooled ceiling combined with displacement ventilation system (STCC-DV) is proposed and investigated in this paper. In STCC-DV system, thermoelectric modules are employed as heating source instead of conventional hydronic pipe, and the combined system dehumidifies the fresh air using a thermoelectric dehumidified system. Both the cooled ceiling and dehumidified ventilation system are powered by PV system. At this stage of our study, we are developing a solar thermoelectric cooled ceiling (STCC) system by using commercially TE technologies. The experiments have been done in a test room using radiant panels whose dimension is 1800 × 600 mm. The results show that the total heat flux and COP of the panel are strongly influenced by operating voltage, ambient temperature and indoor temperature. The total heat flux of the STCC system in cooling mode is higher than 60 W/m^2 and the system COP can reaches 0.9 under operating voltage 5 V. In heating mode, the total heat flux of the STCC system under operating voltage 4 V is higher than 110 W/m^2 and the COP of the system can reaches 1.9. This simply and environmentally friendly system is promising and worthwhile being applied to for low carbon buildings climate control.

1. Introduction

As people spend more and more time in buildings than before, indoor air quality (IAQ) and thermal comfort attract increasing attention. Heating, ventilating and air-conditioning (HVAC) systems that provide high indoor air quality and thermal comfort become very important. However, HVAC systems often consume large amounts of energy [1]. In other words, comfortable indoor environment is paid by energy consumption. Therefore, it is important to investigate the possibility of attaining improved indoor environmental quality efficiently without increasing energy consumption or indeed decreasing energy consumption. One of the HVAC systems that attracted attention for its potential for energy savings while providing high indoor air quality and thermal comfort is a combined cooled ceiling and displacement ventilation (CC/DV) system [2].

In CC/DV system, ventilation and cooling tasks are separated. The cooled ceiling (CC) panels removes parts of sensible cooling loads, while displacement ventilation (DV) system removes pollutants, latent cooling loads and another part of sensible cooling loads. The CC removes sensible cooling loads by convection and radiation with minimum possible disturbances to the stratified air flow [3,4]. Therefore, it is possible to achieve high indoor air quality and thermal comfort in the occupied zone. In addition, the relatively high chilled water temperature used by the CC system means higher chiller coefficient of performance, thus reducing energy consumption. Owing to these advantages the CC/DV system has attracted much attention in recent years [5,6].

Similar to conventional air conditioning systems, existing CC/DV systems still rely on the conventional electric driven air-conditioning and electricity generated from the fossil fuels, which have some disadvantages as following: (1) electric-driven air-conditioning consume too much energy. To meet their demands, fossil fuels are burned to generate electricity, which causes greenhouse effect and continuously worsen global warming, in turn the demand of air-conditioning would be further increasing. (2) The refrigerant of traditional air conditioner, Freon, once leaked, will cause

Abbreviations: COP_{sc}, system cooling coefficient of performance; COP_{sh}, system heating coefficient of performance; I, applied current of TE module (A); Q_c, The cooling capacity of the TE modules at the cold junction (W); Q_h, The heating capacity of the TE modules at the hot junction (W); T_a, ambient temperature of (°C); T_c, cold side of temperature of thermoelectric module (°C); T_h, hot side temperature of thermoelectric module (°C); Ti, air temperature of indoor (°C); T_{ms}, mean surface temperature of STCC (°C); ΔT, temperature difference of thermoelectric module (°C); V, applied voltage of TE module (V).

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irreversible damage to the ozone sphere and make life suffer from ultraviolet radiation. Hence a novel solar thermoelectric cooled ceiling (STCC) integrated with displacement ventilation (DV) is proposed. A PV system are used to power the thermoelectric cooled ceiling and thermoelectric dehumidified ventilation system, thus it can reduce the utilization of fossil fuel consumption and harmful.

Thermoelectric generator [7] and thermoelectric cooler (TEC) [8,9] are the two major operating models applying thermoelectric material. As a solid-state heat pump, thermoelectric cooler system can be powered directly by a photovoltaic (PV) without the help of AC/DC inverter, which greatly reduces the costs. Meanwhile the system is Freon free, causing no harm to the environment. Therefore, the thermoelectric coolers and the solar cells combined technology are beneficial to energy conservation and environment protection [10–12]. Several studies on the performance of the combined systems of the thermoelectric cooler and the solar cells have been carried out. Dai et al. have studied the performance of a solar TE refrigerator [13]. Cheng et al. tested a solar thermoelectric cooling system with a waste heat regeneration unit for green building application [14]. Wahab et al. designed a portable solar TE system, and found that system performance was strongly dependent on the hot and cold sides' temperature of the TE modules [15]. Xu and Van Dessel fabricated and tested an active thermoelectric window system [16]. In their studies on solar thermoelectric cooling, a number of dates and analyses of great significance have been provided.

The main significance of this paper is to study the solar thermoelectric cooled ceiling integrated with dehumidified ventilation technology in the application of low-carbon buildings. Compared with traditional air conditioner, both the thermoelectric cooled ceiling and thermoelectric dehumidified ventilation system can be directly powered by PV system, thus it reduces the utilization of fossil fuel consumption and harmful. It not only takes advantage of radiant heat transfer as a comfortable, healthy and energy efficient way to remove thermal loads, but also operates in a more environmentally friendly manner. The system is a better choice for building climate control under the background of the recent severe haze weather in China. Thus, it can be applied in a vast area.

2. Experimental apparatus

2.1. System description

The solar thermoelectric cooled ceiling combined with displacement ventilation system proposed for space climate control is shown in Fig. 1. In STCC-DV system, the solar thermoelectric cooled ceiling (STCC) adopts thermoelectric cooler instead of hydronic panels as radiant panels, which is burdened with removal of a large fraction of sensible cooling load. The TE modules are connected in series and sandwiched between the aluminum radiant panel and heat pipe sinks in STCC. The heat sinks are used to dissipate heat for TE modules. The fan can provide forced air convection to help the TE modules to release heat more efficiently into the atmosphere. By controlling the direction of the current, the functions of cooling and heating can be easily achieved.

The combined system dehumidifies the supply fresh air using a thermoelectric dehumidified ventilation system. The thermoelectric dehumidified ventilation system is responsible for removal of a small fraction of sensible cooling load and all latent cooling loads. As shown in Fig. 1, the dehumidified ventilation system was composed of a thermoelectric modules heat exchanger made by thermoelectric modules, fans, and flat-fin heat sinks. In summer, the fresh air side behaves as cold side, while the exhaust air side is hot side. The fresh air is cooled down when it flows through heat sink into the indoor. At the same time, the exhaust air cooled down the heat sink on the other side of the TE modules. In winter, reverse the cold side and hot side by changing the direction of the current. The fresh air is heated up and while the exhaust air is cooled down. Therefore, thermal energy can be recovered from the exhaust air and the fresh air could be handled in high energy efficiency [17].

2.2. Experiment setup

In our previous studied, a thermoelectric dehumidified ventilation system was developed. A number of experiments have been completed under different operating conditions in order to verify the DV system has the ability to dehumidify the supply fresh air. At this stage of our study, we are developing a STCC system as shown in Fig. 2. The STCC is constructed in the climate test room which is located inside a larger room with stable but not controlled temperature. The experimental room is an open of 2.53 m^2 (2.3 m × 1.1 m) and an internal height of 2.7 m. The STCC was composed of a 1.8 m × 0.6 m aluminum plate and TE modules with the cold side attached directly to the aluminum plate acting as a cooling panel. The number of the TE modules used will be determined based on the operating voltage and the cooling capacity of the STCC system. According to the performance of the TE modules purchased from FERROTEC Corporation [18], the operating voltage 4–6 V is suitable for STCC system in order to get an excellent performance. Therefore, ten TE modules are used in the STCC system, and the TE modules are uniformly distributed arrangement in the aluminum panel, and two times five TE modules were connected in series, with both series connected to the DC power sully in a parallel circuit as shown in Fig. 2. The size of TE modules is 39 × 39 × 3.8 mm, with 127 thermoelectric couples of bismuth telluride and ceramic surface, type of 9500/127/060 B. And the properties of TE modules are list in Table 1.

The effectiveness of the heat sink at both the cold and the hot side of the thermoelectric modules are crucial to the operation of the STCC-DV system. The heat sink should be designed to minimize the thermal resistance, and should be capable of removing

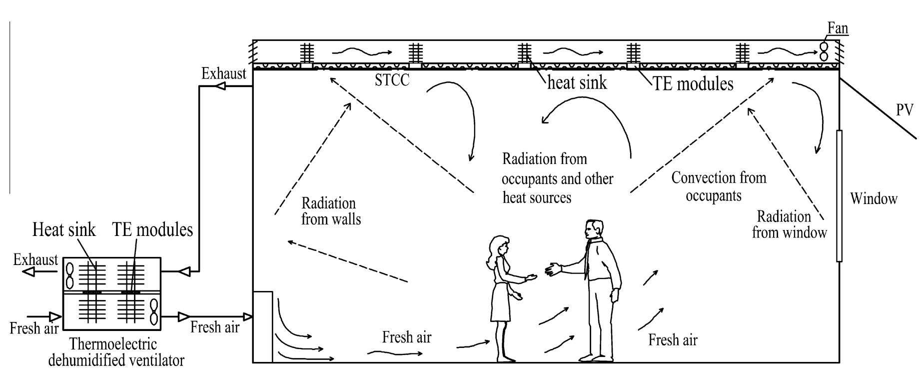

Fig. 1. The schematic of STCC-DV system.

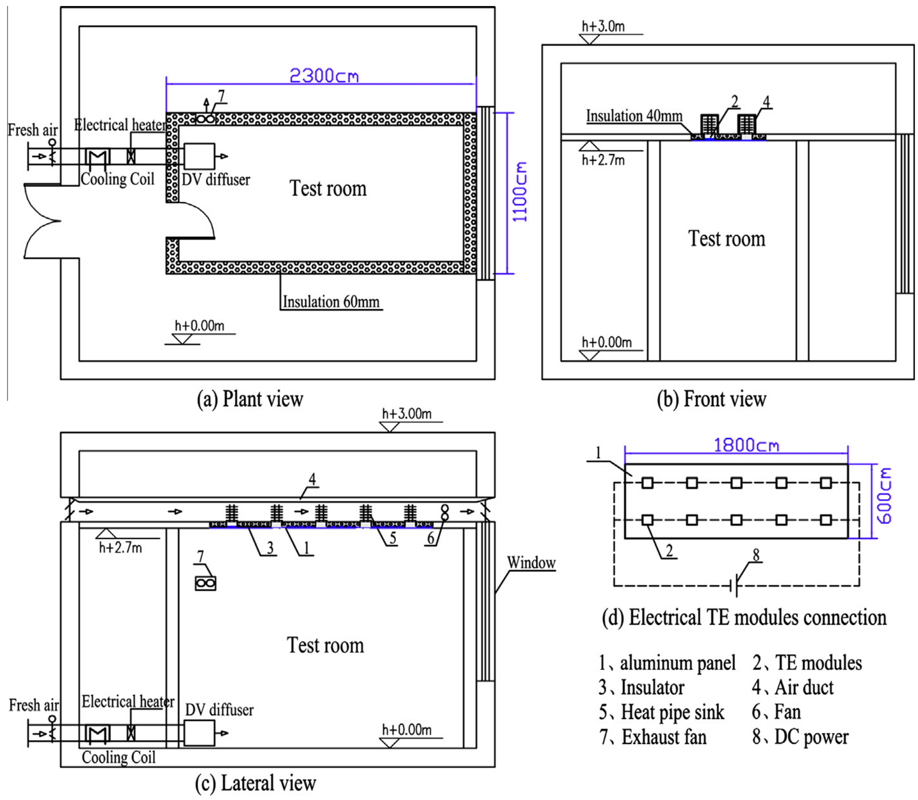

Fig. 2. Test room: (a) plant view, (b) front view, (c) lateral view and (d) electrical TE modules connection.

Table 1
Properties of the thermoelectric modules.

TE module	Number of elements, N	ΔT_{max}	S[a] (V/K)	R[a] (Ω)	K[a] (W/°C)
9500/127/060 B	127	72	0.05	2.36	0.51

[a] At the average temperature of 20 °C.

sufficient heat from both cold and hot sides. In order to get an excellent performance, ten (heat pipe, embedded fin) heat sink units were attached directly to the hot side of each TE modules in cooling mode. The heat pipe sink for TE modules heat dissipation is a commercial heat pipe, called yinhua. Two fans were used to provide forced air convection, and the power of each fan is 6 W (the operating voltage is 24 V and the current is 0.25A), and the air flow of fan is 154 m^3/h (the air velocity is 5.4 m/s in air duct). Moreover, a 4 cm-thick insulation layer was laid on the back surface of the STCC panel so that heat transfer from the TE modules to the air in the upper zone was minimized.

An cooling coil (the cold water is supplied by an air-to-air heat pump) and electrical heater are used to control the temperature of the fresh air, which permits room air temperature to be fixed to an approximately constant value in tests, and a small box with a lower opening was constructed in front of the supply section in order to avoid effects caused by high supply air velocity affecting convective phenomena inside the room. And an exhaust fan was set for the test room. In this way hot or cooled air slows down inside the box and enters the occupied zone with a very small velocity, and quite homogeneous air temperature conditions are achieved inside the test room and free convection is assured.

2.3. Measurement equipment

All the temperature values are tested and recorded with a paperless recorder and a PT100 temperature sensor, and the accuracy of this temperature PT100 is ±0.1 °C. A total number of 22 probes were used to measure cold side and hot side of the thermoelectric modules, ceiling surface temperatures. They were conveniently coated with an insulation layer and stuck to the surface by a small piece of adhesive tape. Besides, four temperature sensors with a radiant protection were placed in the vertical direction in the center of the room in order to observe air temperature stratification. The ambient air temperature was also registered by means of an extra sensor. The operating voltage was directly controlled by a DC power. The input operating voltages and currents of the TE modules are read through the DC power display. In addition, the air velocity and air humidity of the test room also be recorded.

3. Calculation method of heat flux

According to the T_c, T_h and the current recorded in the tests, the amount of heat transferred by each TE module can be calculated according to Eqs. (1) and (2) [18,19]:

$$Q_c = SI(T_c + 273.15) - \frac{1}{2}I^2R - K(T_h - T_c) \quad (1)$$

$$Q_h = SI(T_h + 273.15) + \frac{1}{2}I^2R - K(T_h - T_c) \quad (2)$$

where I is the current; T_c is the cold-side temperature; T_h is the hot-side temperature; S is the module's electrical resistance ($R = 2Na$); R is the module's electrical resistance ($R = 2N\sigma/G$); and K is the

module's thermal conductance ($K = 2NkG$). S, R and K are the temperature dependent parameters. N refers to the total number of TE elements used in each module. G is the so called geometric factor, and a, σ, K are the material properties for the specific the type of the TE element. The values of S, R, K vary with the average temperature of the thermoelement Tm; the relations are supplied by [18].

The total heat flux in cooling mode (q_{tc}) and the total heat flux in heating mode (q_{th}) are the summation of convective heat flux and radiant heat flux, respectively. For solar thermoelectric cooled ceiling system, the total heat flux transferred from the TE modules to the radiant aluminum panel is the total heat flux of the solar STCC system, which can be calculated according to Eqs. (3) and (4):

$$q_{tc} = \frac{nQ_c}{s} \tag{3}$$

$$q_{th} = \frac{nQ_h}{s} \tag{4}$$

where n is the number of TE modules; s is the area of the radiant panel.

The system coefficient of performance of the TE module in cooling mode (COP_{sc}) is given by:

$$COP_{sc} = Q_c/(P + W) \tag{5}$$

The system coefficient of performance of the TE module in cooling mode (COP_{sh}) is given by:

$$COP_{sh} = Q_h/(P + W) \tag{6}$$

where P is the input electric power; W is the power of the fan.

4. Experimental investigations

The performance of the STCC system is tested under different operating conditions. The temperature of the test room (Ti) was keep at 25 ± 2 °C in cooling mode and 18 ± 2 °C in heating mode when tested. According to the T_c, T_h and the current recorded in the tests, the amount of heat transferred by each TE module can be calculated according to Eqs. (1) and (2), and then the total heat flux of STCC can be calculated by Eqs. (3) and (4) respectively. Thus the coefficient performance of the system can be calculated through Eqs. (5) and (6).

Figs. 3 and 4 present the performance of the STCC system under different voltage and different ambient temperature (T_a) in cooling mode and heating mode. It can be observed that, the surface temperature (T_{ms}) of radiant panel is decreasing quickly to a certain value after half an hour and then keep stable under different voltage in cooling mode. In heating mode, the temperature changes rapidly after the systems working about twenty minutes, and then keeps stable.

The increasing of the operating voltage decreases the surface temperature of the STCC system in cooling mode and increases the surface temperature in heating mode. From Figs. 3 and 4, it can be observed that a change in supply voltage has a larger effect on the surface temperature of the STCC system in heating mode than in cooling mode. The surface temperature of the STCC system is about 18 °C when the voltage is 5 V in cooling mode, and when the operating voltage increasing to 6 V, the temperature is about 16.5 °C. When operating in heating mode, the temperature of interior surface of the STCC system increase from 33 °C to 38 °C when the operating voltage increase from 4 V to 5 V.

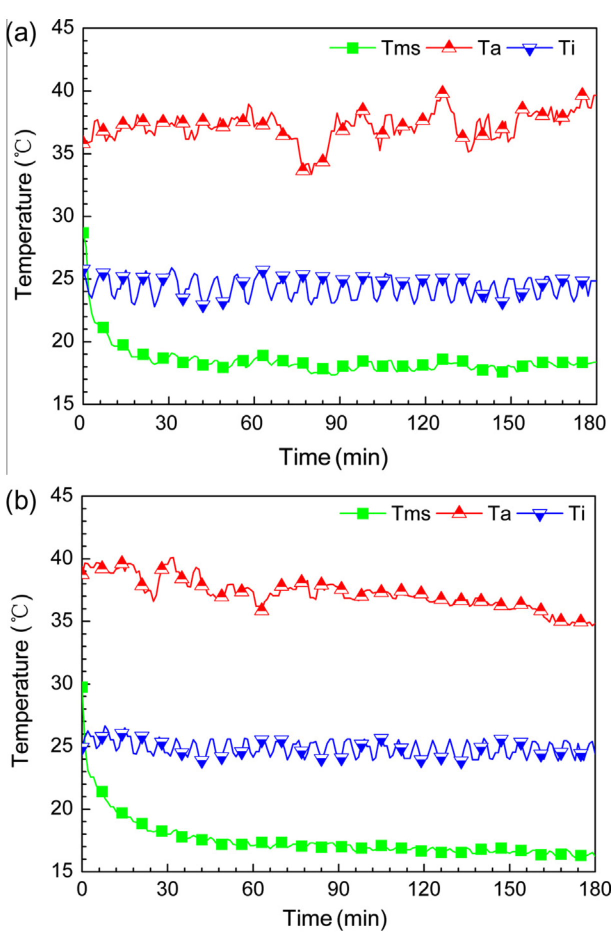

Fig. 3. Performance of the STCC system in cooling mode (a) 5 V and (b) 6 V.

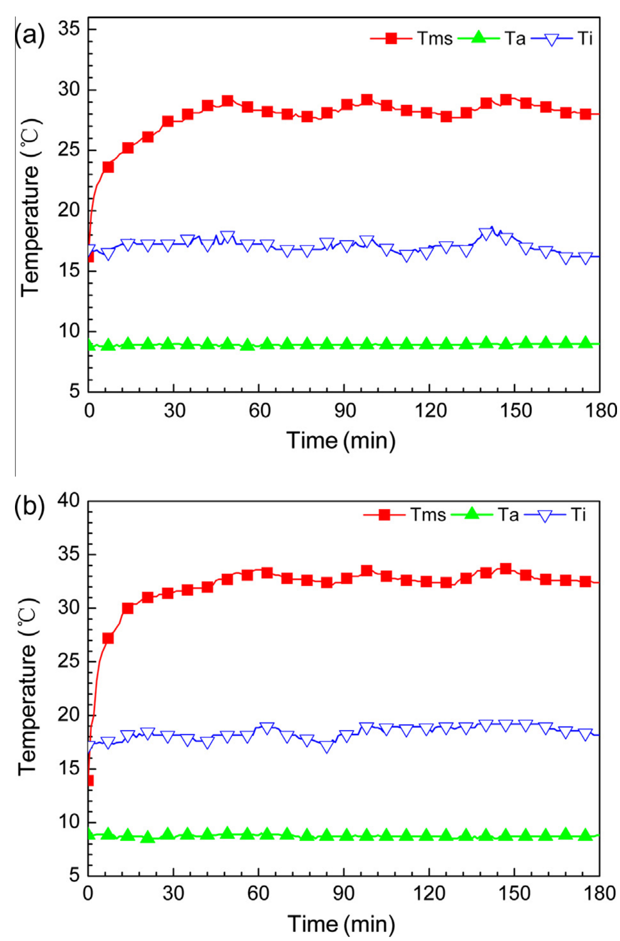

Fig. 4. Performance of the STCC system in heating mode (a) 4 V and (b) 5 V.

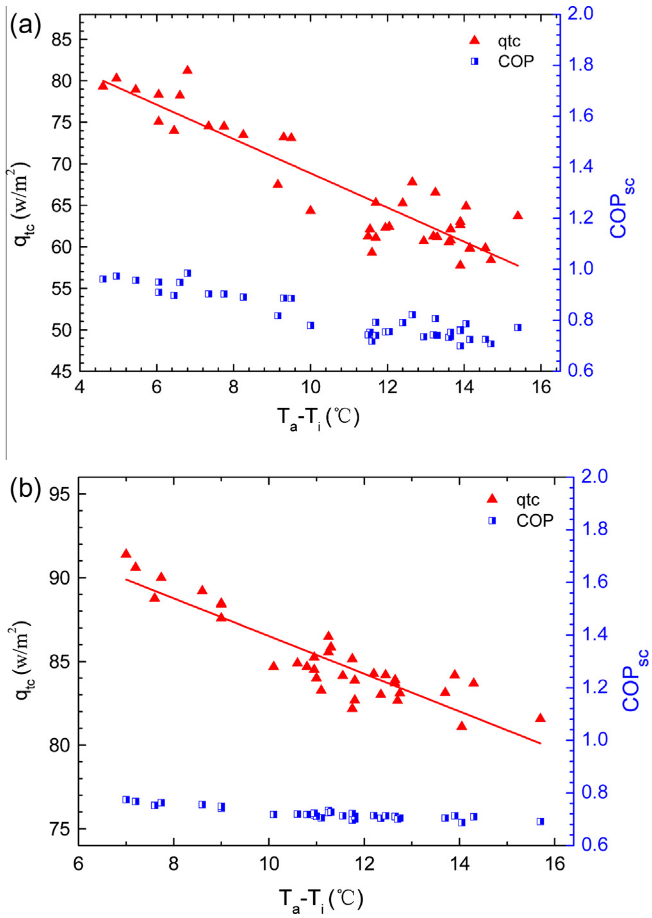

Fig. 5. Cooling capacity and coefficient performance of the STCC system (a) 5 V and (b) 6 V.

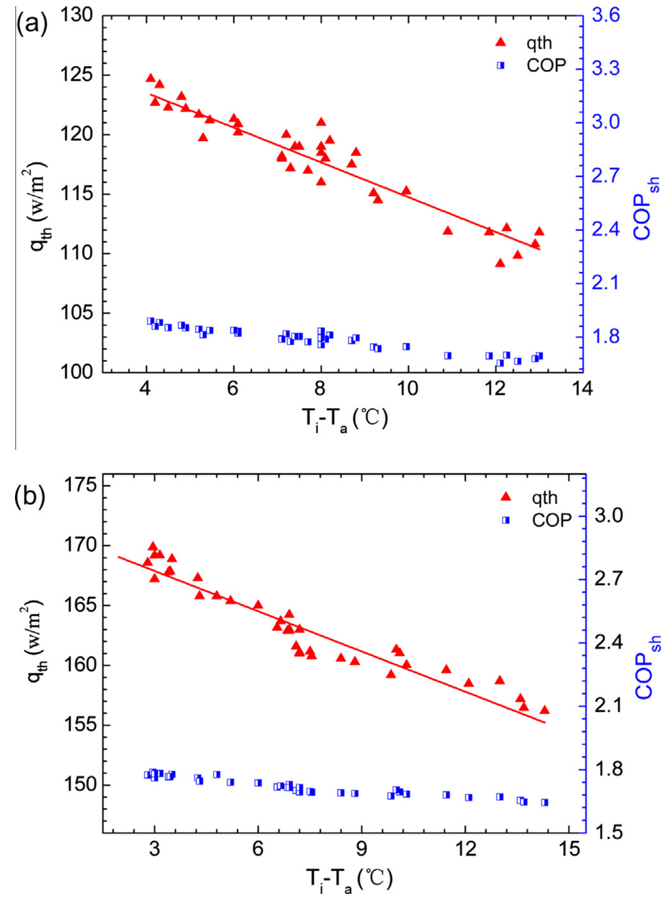

Fig. 6. Heating capacity and coefficient performance of the STCC system (a) 4 V and (b) 5 V.

Figs. 5 and 6 show the cooling capacity, heating capacity and coefficient performance of the STCC system under different temperature difference of indoor temperature (T_i) and ambient temperature (T_a). As can be seen, total heat flux increases with the decreasing temperature differences as expected. This is because the smaller the temperature difference of indoor temperature and ambient temperature is, the smaller the temperature difference of the cold and hot side of thermoelectric modules is, thus the better performance of the STCC system is. According to the tested results, an total heat flux from 80 W/m^2 to 92 W/m^2 can be reached when the temperature difference is increase from 7 °C to 16 °C with operating voltage 6 V in cooling mode. And an total heat flux from 156 W/m^2 to 170 W/m^2 can be reached when the temperature difference is increase from 3 °C to 14 °C with operating voltage 5 V in heating mode, and more effective heat flux can be achieved by increasing operating voltage to satisfy the requirements for space heating and cooling.

As a solid heat pump system, the coefficient performance of the STCC system can be calculated by the total power input and the energy output. As shown in Figs. 5 and 6, the coefficient performance (COP) is affected by temperature differences of the cold and hot side. Increasing the temperature difference of indoor temperature and ambient temperature increases the temperature difference of the hot and cold side of TE modules, and therefore decreases the system COP. The coefficient of the performance can reach 0.9 under operating voltage 5 V in cooling mode and 1.9 under operating voltage 4 V in heating module.

5. Discussion

5.1. Coupling with thermoelectric dehumidified ventilation system

To show the feasibility of the combined system in hot and humid climate like china, the following assumed office building conditions were used to analyze the combined system [20]: the cooling load was 100 W/m^2 and maximum occupancy was 0.15 person/m^2. Weather conditions of Beijing were used. The designed indoor air conditions were dry bulb temperature of 25 °C and relative humidity of 50%. Fresh air flow rate of 30 m^3/h per person was assumed to maintain good indoor quality. Each person produced moisture load is 60 g/h, since no other moisture sources were assumed present, the moisture load is 9 g/(h m^2). According to the tested results, an effective heat flux (Q_c-effective) can be reached 80 W/m^2 of radiant panel area in cooling mode. At present test, only 1.08 m^2 areas in 2.53 m^2 of the floor are covered by radiant panel, and then if the radiant panel covers all the ceiling area, the STCC can afford 80 W/m^2 for floor area. Therefore, the DV system should afford 20 W/m^2 to attain the required cooling capacity. The supply fresh air is 6 m^3/(h m^2). To remove the moisture and afford the cooling load 20 W/m^2 produced indoor environment, supply fresh air with dry bulb temperature 15 °C and absolute humidity 8.5 g/kg was provided. And the cooling capacity of DV system is about 100 W/m^2. The coefficient of performance of DV system was found to be over 2.5 in cooling mode in Ref. [17], so the electrical power consumed by the DV is about 40 W/m^2. In practical application, similar to conventional radiant cooling

system, STCC system also has condensation risk. To avoid condensing, the STCC surface temperature should be at least 1 C higher than the dew-point temperature of indoor air [21]. According to the test results, the interior surface temperature is very sensitive to the current, so the interior surface temperature can be rapidly changed by adjusting the input current or on–off control of multiple thermoelectric modules. Once the condensation risk is detected, the surface temperature can be adjusted rapidly so that the risk can be reduced timely.

5.2. Power supplying control

Figs. 3 and 4 show the mean surface temperature (T_{ms}) of STCC system is sensitive to the operating voltage in cooling mode and heating mode. Therefore, the mean surface temperature of the STCC system can be rapidly changed by adjusting the operating voltage of the thermoelectric modules. Once the indoor room environment is too cold or too hot, the mean surface temperature of STCC system can be adjusted rapidly so that the temperature of the room can be kept at required point. In the present experiments, the STCC-DV system is powered by a DC power supply, this power supply will be replaced by a PV panel system in further studies. In daytime, the PV systems receive solar energy and turn it into electric power supplied to thermoelectric modules. If the electric power production is larger enough, the power surplus can be accumulated in storage battery besides driving the STCC-DV system. And if the PV systems cannot produce enough electric power, for example, in rainy days, the storage battery may offer a makeup. The PV system and battery is controlled by an auto-switcher, which can play a role to maintain the energy conversion process in most optimized way.

5.3. System COP

The COP of conventional thermoelectric air conditioner is typically about 0.4 in cooling mode and 1.4 in heating mode [10,11]. According to test results, the STCC system COP of the novel system can reach 0.9 in cooling mode and 1.8 in heating mode, which is higher than that of the traditional thermoelectric air conditioner. This is because the cold side temperature of thermoelectric modules required by the combined system is higher than that required by the conventional system. Higher cold side temperature means higher coefficient of performance (COP). And since the DV system can recovery heat from exhaust air, the coefficient of performance of DV system was found to be over 2.5 in cooling mode and heating mode [17]. At present, the heat of the hot side in cooling mode is carried away by air convection. In order to enhance heat transfer, water cooled forced convection heat exchangers will be applied in the future study. Additionally, the performance of the STCC-DV system can be further improved by improving module contact resistances and thermal interfaces [22–24]. What is more, the TE performance is closely related to the figure of merit of thermoelectric materials, ZT, the TE modules used in this paper has a ZT of 0.61, which is not high considering the progress of TE technology. It is achievable since the latest quantum well materials have a ZT as high as 2.4 at 300 K [25], and when TE materials that have a ZT = 2, the COP of TE coolers can reach that of vapor-compression coolers in climate-control applications [26].

5.4. Practical issues when coupling the STCC system with a PV system

According to the experimental results, the total heat flux of the STCC system is reasonable when coupling with thermoelectric dehumidified ventilation system under operating voltage at 6 V in cooling mode and 4 V in heating mode. This indicates that TE system and fans in STCC system require approximately 100 W/m^2 of input power to keep the total heat flux at 80 W/m^2 (cooling mode), and 58 W/m^2 to keep the total heat flux at 110 W/m^2 or higher (heating mode), and the electric power consumption of DV is about 40 W/m^2 according to above results of discussion. So the output power of the PV system should approximate 140 W, or near 1.12 kW h, in order to allow the TE system to work sufficiently in daytime, or 8 h. As STCC-DV systems rely on solar energy, it is indispensable to have a means of energy storage available when no solar energy is available. Usually, batteries can be used to storage of electrical energy for STCC-DV system. Therefore, the general output power analysis is more or less independent of time, and only affected by the total solar radiation and panel size. For example, the average solar radiation for Harbin in China over January is about 5.3 kW h/(m^2-day), and a typical crystalline silicon PV panel has an efficiency of approximately 18%, so the electric quantity per day generated by a PV with an area of 1 m^2 is about 954 W for each day. However, the battery charging efficiency is very low under low voltage charging state in practice application. In order to keep the system working stably, the total area for the PV panels maybe only reached to 2 m^2 can satisfy the energy demand of STCC-DV system.

6. Conclusions

In this study a novel solar thermoelectric cooled ceiling combined with displacement ventilation system (STCC-DV) is proposed and tested. The thermoelectric modules work as ceiling panel and dehumidified system by taking solar energy. The novel system has a lot of advantages including Freon free, silent, and clean due to no moving part. Moreover, it can be directly powered by a PV system with no inverter. A test room has been built for testing the feasibility of this system, and the experimental results are provided. The conclusions reached in the present study can be concluded as followings:

(1) The results show that the performance of the STCC system is strongly influenced by operating voltage, ambient temperature and indoor temperature. Increasing the operating voltage increases the total heat flux. Decreasing the temperature difference of ambient temperature and indoor temperature (T_a–T_i) significantly increases the total heat flux and slightly increases the system COP in both cooling and heating mode.

(2) For the typical test condition, the total heat flux of the STCC system in cooling mode under operating voltage 5 V and 6 V are higher than 60 W/m^2 and 80 W/m^2 restrictively. In heating mode, the total heat flux of the STCC system under operating voltage 4 V and 5 V are higher than 110 W/m^2 and 150 W/m^2 restrictively. And more total heat flux can be reached by increasing operating voltage.

(3) The STCC system COP can reach 0.9 in cooling mode and 1.9 in heating mode, which is more efficient than that of traditional thermoelectric air conditioner. And a higher coefficient performance can be achieved by using higher ZT value of TE modules. The TE modules used in this paper has a ZT of 0.61, which is not high considering the progress of TE technology. And when TE materials that have a ZT = 2, the COP of TE coolers can compete with vapor-compression coolers in applications.

(4) Overall the system can be operated using renewable energies, in particular PV system which produces DC electricity. The system is a better choice for building climate control under the background of the recent severe haze weather in China.

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